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ORBIT DETERMINATION OF A NEAR-SYNCHRONOUS SATELLITE FROM PASSIVE RANGE OBSERVATIONS

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13. ABSTRACT

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1. INTRODUCTION

This document reports on an experiment to determine the ephemerides of a near-synchronous satellite from observations which are known as passive range measurements. A passive range tracking system consists of measurements taken at tracking sites of the times of arrival of electromagnetic signals transmitted at regular intervals from the spacecraft. The time interval between the instant the signal leaves the spacecraft and when it arrives at a tracking site is a measure of the range to the spacecraft. This system differs from the usual radar range measurement system in that it is open loop; the ground stations are radio passive. The typical radar range measurement system is closed loop in which the ground station transmits a signal which is reflected (either actively or passively) from the spacecraft. Inherent to the passive range technique is the necessity to maintain time synchronization between the clocks at each of the tracking sites and the spacecraft. It is possible to maintain synchronization of the station clocks by several means. These are, 1) to hand carry portable clocks from station to station, 2) to utilize VLF radio transmission from timing reference stations such as the WWV station at the National Bureau of Standards and 3) to use the timing transmissions from the Navy Navigation Satellite System. The calibration of the satellite clock is distinct from the station clock calibration because the satellite is inaccessible and presumably at an unknown location. Consequently, it is necessary to estimate the satellite clock parameters as part of the orbit determination procedure.

The DODGE (Department of Defense Gravity Experiment) satellite program was designed primarily to demonstrate gravity-gradient stabilization near synchronous altitudes and to determine the adequacy of theoretical analyses by correlation between digital simulation results and experimental attitude data [1].* A complete description of the mission as well as the satellite and ground instrumentation is given in [2].

*Brackets denote References at end of paper.

The nominal prelaunch orbit characteristics were an altitude of 18,200 nautical miles and an inclination of 7 degrees. This would imply an orbital period of approximately 22.186 hours and a period relative to an earth-fixed meridian of approximately 13.2 days. At a latitude of 39 degrees, which is the location of the satellite command facility at the Applied Physics Laboratory, the spacecraft would be in constant view for about 5.6 days, reappearing after 7.6 days.

The accuracy requirement for the ephemerides was arrived at after considering several aspects of the satellite mission. A posteriori ephemerides are necessary for the stabilization studies and the reduction of telemetry and video data especially that from which the attitude of the spacecraft is to be determined. A maximum a posteriori position error of 100 nautical miles (4.6 milliradians) was established as a realistic goal for the DODGE satellite. By present day technology this is not a demanding criterion, but the experiment was to examine the feasibility of the method with the intention of improvements on subsequent spacecraft.

2. TRACKING METHODOLOGY

The techniques most frequently used to obtain satellite tracking data can be grouped into three categories: angle, range-rate and range. There are several different methods by which data of each type can be obtained. For low to intermediate altitude satellites, data from any one of these techniques would be sufficient to establish an orbit. For example, the Applied Physics Laboratory has developed the Navy Navigation Satellite System. Here the measurement of the Doppler effect on a VHF carrier (range-rate) provides the data from which the satellite ephemeris is determined. The precision of the a posteriori ephemerides of these navigation satellites, which are at a nominal altitude of 600 nautical miles, is better than 20 meters [3].

While the Doppler method works well for low altitude satellites, degradation is to be expected for high altitude satellites where the magnitude of the Doppler effect is reduced and the measurement errors remain the same. In addition, for a truly geostationary satellite, there would be no measurable Doppler effect and the longitude (along-track position) of the satellite would be indeterminate.

Because of the existence of the Navy Doppler tracking stations and the expertise realized in the development of the Doppler tracking technique, studies were first undertaken to establish the merit of Doppler tracking of the DODGE spacecraft [4]. These studies showed that while it might be possible to achieve the required accuracy of 100 nautical miles, the confidence in doing so was not high. Consequently, an auxiliary means for tracking, designated the DODGE Time Recovery System (DTRS), was developed [5].

Basically, the DTRS provides satellite instrumentation for periodic transmission of a "time pulse", a discrete identifiable modulation of the down-link carrier. The control of this transmission is provided by the satellite's automatic programmer which, in turn, uses the satellite's ultrastable oscillator as a basic time and frequency reference. Appropriate equipment was designed and installed at four existing TRANET stations to receive these special transmissions.

3. TRACKING SYSTEM

3.1 Satellite and Station Instrumentation

Fig. 3.1 is a block diagram of the satellite instrumentation used in generation and transmission of the time pulses.

The time pulses appear as a 60 degree phase modulation of the 240 MHz downlink carrier. Specifically, the time pulse waveform for any individual transmission consists of 128 cycles of a square wave of frequency 325.5 Hz. The first 126 cycles have one phase. After the 126th cycle, there is a 180 degree phase shift followed by two more cycles. This phase shift is the signal feature which is detected and measured by the ground station equipment. This waveform is shown in the top half of Fig. 3.2.

The timing mark generator shown in Fig. 3.1 transmits a 128 cycle burst of 393 milliseconds duration. This sequence is repeated every 3.2 seconds. The automatic programmer sequences these bursts into the total schedule of downlink transmissions by controlling the modulation index control unit. The programmer starts automatically once per hour and runs the satellite for ten minutes. It will then shut off unless commanded otherwise. During this 10 minute period, three time bursts will be sequenced into the transmission. These occur at the end of consecutive 200 second intervals, as shown in the bottom half of Fig. 3.2. There are thus, under normal automatic operation, three discrete pulses per hour or 72 data points per day.

The automatic programmer and the timing mark generator obtain their frequencies by dividing down the signal from the stable 5 MHz oscillator. Thus, the time interval between consecutive time pulses is tied directly to this oscillator as a reference. For this reason, the oscillator must have been turned on and allowed to stabilize before useful data can be obtained.

Each tracking station participating in the time pulse tracking network is equipped with a unit capable of acquiring the time burst waveform and detecting the phase reversal. This detection triggers a reading of the station ultrastable clock. This reading is the basic measurement.

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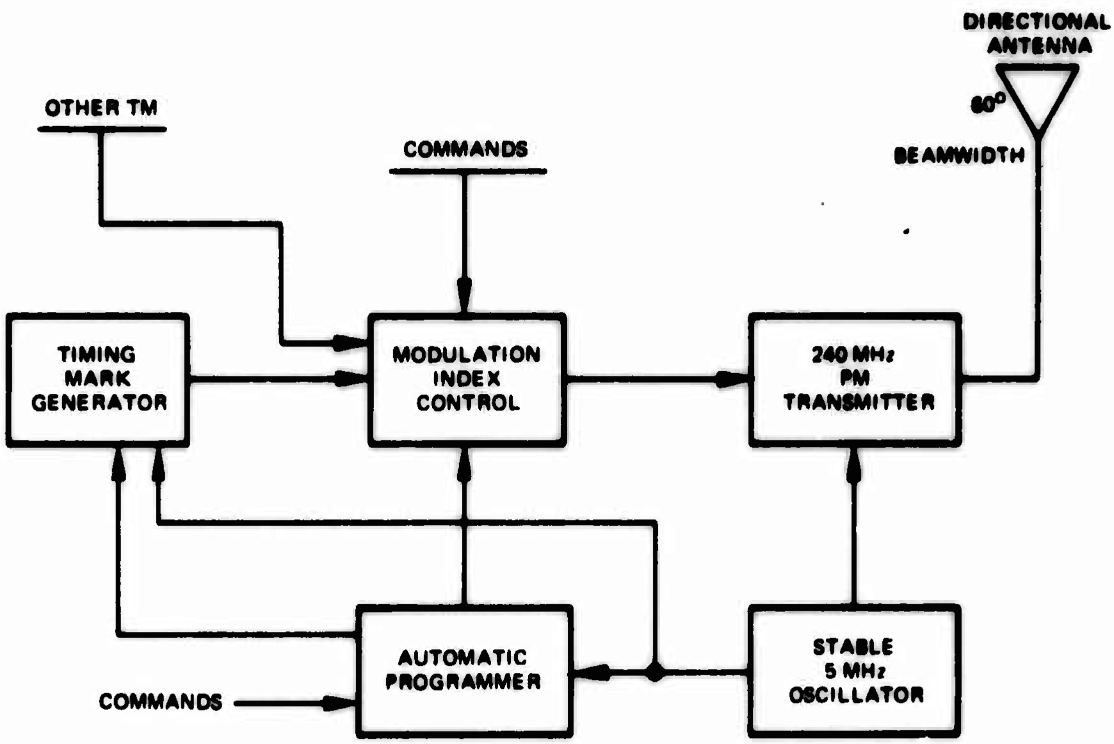

Fig. 3.1 DODGE SATELLITE TIME PULSE SYSTEM

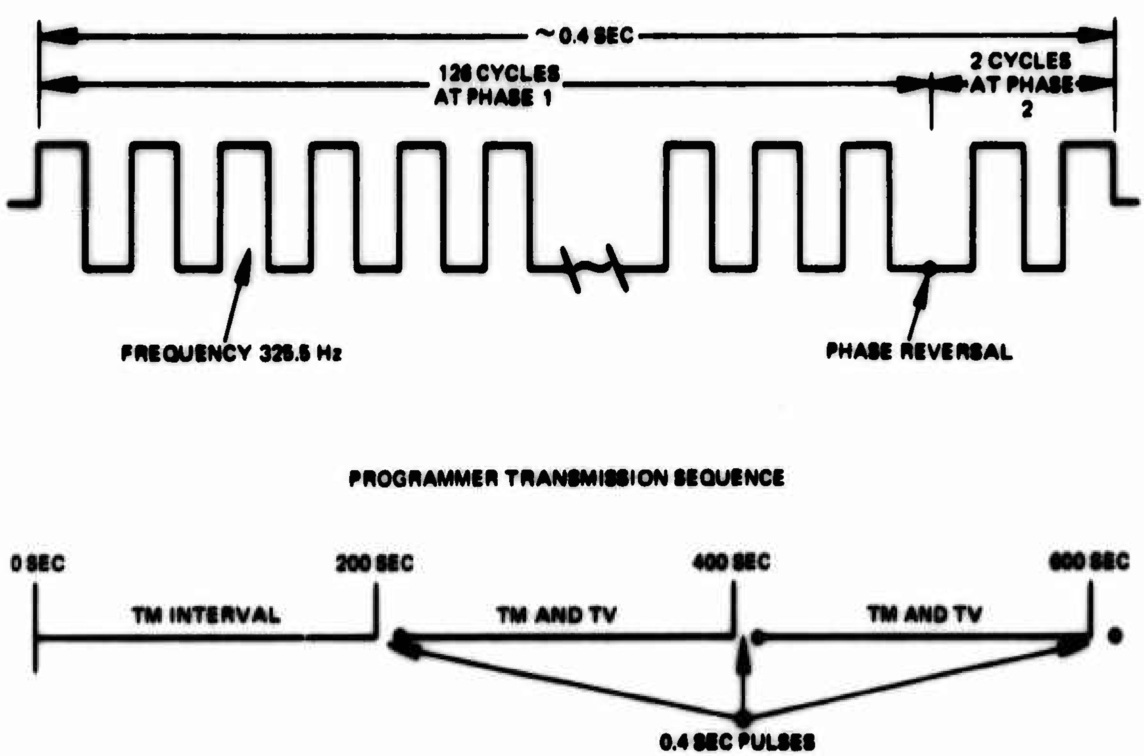

Fig. 3.2 DODGE TIME PULSE WAVEFORM

Corrected for measured delay in the receiving equipment and for epoch and drift in the station clock, the reading becomes a time pulse data point. The DTRS ground system tests are described in detail in [6].

Four stations of the TRANET system have been equipped with these DTRS units: station 008, San Jose dos Campos, Brazil; station 013, Misawa, Japan; station 112, Smithfield, Australia; and station 911, Howard County, Maryland. The units are able to record the time of recognition of the time burst from the satellite with a one microsecond resolution.

An obvious basic requirement is that the station clocks in this network be synchronized to high precision. This means that an epoch must be established at each station with respect to a common reference. Similarly a common clock rate reference must be used.

The epoch is best established by periodic visits to the station with a portable atomic clock which yields time transfers accurate to a few microseconds. A description of this process and results of visits to the stations are discussed on pp. 43-50 of [7]. The frequency or clock rate reference is obtained by station tracking of standard VLF transmissions. For the time pulse experiment, the Pacific stations at Smithfield and Misawa used the 13.6 KHz transmissions from Haiku, Hawaii; this is an OMEGA station. The station at San Jose dos Campos, used the 12 KHz OMEGA signal from Trinidad, while the Howard County clock is maintained in synchronism with the U.S. Naval Observatory. A discussion of this frequency tracking and associated instrumentation at a station is presented in Section 2, Chap. 9 of [5].

3.2 System Error Sources

There are a number of errors in the time pulse tracking process described above which will cause errors in the orbit determined from such data. In this subsection, these are summarized, leaving the mathematical representation for the next subsection.

First, there is the stability of the satellite instrumentation, particularly its 5 MHz ultrastable oscillator. It is also possible to interrupt the regular sequence of time pulses by commands which reset the automatic programmer or switch between the pair of oscillators. These

are discrete events that are easily recognizable in the data through the large discrepancies in programmed interpulse intervals which they cause. However, they must be guarded against because they break up the span of data that can be employed in tracking.

The ultrastable oscillator units used on DODGE are of the same quality as those used in the Navy Navigation Satellite System. They can thus be expected to maintain short-term drift rates of a few parts in 10^{11} and long-term drift rates of 1 or 2 parts in 10^{10} per day. Normally, one would not expect such drift rates to be constant over long periods of time, i.e., days or weeks. Rather, one would expect them to have something of a "random-walk" behavior, changing in direction and magnitude at random and unpredictable times.

A drift rate of 2 parts in 10^{10}, maintained over a one-day interval, would result in a 9 μsec error in programmed time of transmission for a pulse. Because of the random-walk character of the drift, it was originally hoped that an error of this size would be rather infrequent. However, as will be discussed later, the data utilized indicated that the satellite oscillator drift was apparently nearly constant over the whole tracking span. Consequently, it became necessary to account for this drift.

The ionosphere introduces variations in the group path velocity of the VHF carrier. These introduce errors in the measured times of arrival of the pulses. The amount of this error is highly dependent on the profile of electron density in the ionosphere, and also on the elevation of the satellite with respect to the station. The electron density profile has a high degree of variability on a diurnal, a seasonal and a geographical basis.

To study the ionospheric refraction error, several profiles were postulated, representing both "ordinary" and "extreme" conditions. The equations representing the transit-time error for 240 MHz signals, in terms of each such profile, were then numerically integrated. The results furnish a spectrum of possible ionospheric errors. These studies are reported in detail in [8]. Suffice it to say that the normal ionospheric error is in the range of a few microseconds and hence was neglected in the orbit determination process.

The remaining system errors are connected with station instrumentation and operation. They fall into three principal areas:

(i) The accuracy with which remotely separated clocks can be synchronized to the common UTC standard.

(ii) The accuracy with which equipment delays can be measured and controlled.

(iii) The signal-to-noise ratios in the DTRS units.

These classes of errors are discussed fully in Section 2, Chap. 9 of [5]. That discussion is summarized here.

The r.f. noise error (iii) can be minimized by employing suitably narrow bandwidths in the tracking filter of the DTRS unit. The phase reversal of the input signal is detected by comparing the input and output of the filter. Due to the narrow filter bandwidth, the output signal continues at its original phase immediately after the phase reversal and hence the input and output signals differ by 180 degrees. A phase reversal detector compares the filter input and output signals and triggers a time measurement on the next filter output cycle. In this way, a white noise bandwidth corresponding to the filter bandwidth is achieved. A calculation given on pp. 9-35 of [5] indicates that, using a filter installed in a temperature controlled oven with a bandwidth of 2.4 Hz, the r.f. noise error should have an rms of at most a few microseconds for the lowest input signal-to-noise ratio.

The design objective for the synchronization error (i) was set at 20 μsec peak-to-peak, i.e., a bias error of no more than 10 μsec relative to UTC at any station. This objective requires careful setting of an epoch by means of a portable clock, as well as consistent, accurate monitoring of the VLF frequency reference. A time and frequency control experiment carried out between a TRANET site, station 103, Las Cruces, and station 911, Howard County, indicated that such accuracies could be obtained in the continental U.S. However, it is less certain how well they could be achieved on a world-wide basis. This is discussed on page 50 of [7].

There are additional problems when, for various reasons, a station loses an epoch which has been established

by the portable clock. A careful examination of station records for frequency tracking is then needed to infer the probable epoch error. It is conjectured that epoch cannot consistently be established much better than 50 μsec under these conditions.

The stations in the DODGE time tracking network reset their clocks daily during tracking periods. Examination of the frequency errors, as determined by comparison against the VLF references, consistently indicates that accuracies better than 1 part in 10^{10} have been maintained. Thus, it seems likely that, from the viewpoint of frequency tracking alone, clock errors should be below the 10 μsec objective. The total epoch error may, however, be several times this amount.

The remaining station error (ii) results from calibration of signal delay in the DTRS unit. This is discussed in [5] and also, in more detail, in [9]. Tests were made to determine equipment delay times as a function of r.f. signal level, receiver loop bandwidth, receiver tuning, AC line voltage variations, and temperature variations. The results in [9] indicate that the dispersion in successive delay measurements is about 6 μsec. This represents variability in delay with respect to a daily mean value. In addition, there is some long-term drift in delay values. Except for the station at Misawa, delay measurements indicate long-term drifts of less than one microsecond per day.

Summarizing this section, the major errors in the measurement of time points arise from satellite oscillator bias and, occasionally, from consistent oscillator drift. To a lesser extent, error is introduced by inaccuracies in synchronizing all stations to a common time base and by lack of precise signal delay calibrations at the various stations.

In principle, one would hope to compensate for satellite frequency offset and drift by solving for these as part of the orbit determination process. However, it must be remembered that, for a given tracking station, a DODGE "pass" is 4-5 days in duration. It seems unlikely that typically the oscillator would have a constant drift rate over so extended a period. Hence, to hypothesize one and attempt to solve for it involves a theoretical error. It is also true that the least squares normal equations used in orbit determination become quite ill-conditioned when drift rate is included as a parameter. Nor is the amount of data

available in a single pass from a single station ordinarily enough to give even a good determination of frequency offset.

4. ORBIT DETERMINATION PROGRAM

4.1 Mathematical Formulation

We consider a time pulse whose distinctive feature, the phase reversal of Fig. 3.2, is emitted from the satellite at UTC instant t_i . Let this pulse be detected by station k at UTC instant τ_{ik} . This implies that all necessary corrections for station clock error, signal delay, etc., have been made. Then, since refraction effects are neglected,

$$\tau_{ik} = t_i + \frac{\rho_{ik}}{c} \tag{4.1}$$

where

$$\rho_{ik} = |\vec{r}(t_i) - \vec{r}_{STA}(\tau_{ik})|$$

and $\vec{r}(t_i)$ is the satellite position at t_i and $\vec{r}_{STA}(\tau_{ik})$ is the station position at τ_{ik} .

It is clear from the discussion in subsection 3.1 that there are two kinds of intervals between any two consecutive time pulses. One is the "small" interval of approximately 200 seconds between consecutive bursts within a given hourly transmission. The other is the longer interval (about 3200 seconds) between the last pulse of one hour and the first pulse of the next hour. Let us denote the exact durations of these two kinds of intervals by $\Delta_1 t$ and $\Delta_2 t$, respectively.

Since we do not know the exact time-varying history of the satellite oscillator's frequency (assuming again that it behaves something like a random walk) we will not know $\Delta_1 t$ or $\Delta_2 t$. However, we can form estimates of them and, perhaps, at least partially correct these estimates by means of the data. Specifically, let our best estimate of the oscillator frequency in Hz be denoted f_o . Since there is a precise known number of oscillator cycles in each of the two kinds of intervals, the current best estimates of the duration of these intervals are

$$\left.\begin{aligned}(\Delta_1 t)_e &= (1{,}006{,}632{,}960)/f_n \\ (\Delta_2 t)_e &= (15{,}986{,}196{,}473)/f_n\end{aligned}\right\} \qquad (4.2)$$

The numerators are the cycle counts built into the timing mark generator and automatic programmer. The subscript "e" denotes estimate. Insofar as the true behavior of the satellite frequency over the tracking span can be characterized as a simple frequency offset of Δf Hz, an improved estimate would be

$$\left.\begin{aligned}\Delta_1^* t &= (\Delta_1 t)_e \left(1 - \frac{\Delta f}{f_n}\right) \\ \Delta_2^* t &= (\Delta_2 t)_e \left(1 - \frac{\Delta f}{f_n}\right)\end{aligned}\right\} \qquad (4.3)$$

Returning to the basic data eq. (4.1), we see that we can replace the left-hand side with

$$t_i = t_0 + \delta t + k(i,1)\, \Delta_1^* t + k(i,2)\, \Delta_2^* t \qquad (4.4)$$

In writing this equation, we are considering that data for a given tracking span has been chronologically arranged and the initial pulse is estimated to have been transmitted at UTC instant t_0 . There will be an epoch error in this estimate, of course, which has been denoted δt in eq. (4.4). After the initial pulse, all subsequent pulses must then have been transmitted at some <u>integer</u> combinations of $\Delta_1 t$ and $\Delta_2 t$ intervals. For the i-th pulse in the tracking span these integers have been denoted $k(i,1)$ and $k(i,2)$. They are, of course, easily determined from the data τ_{ik} since $\delta t \ll \Delta_1 t$.

Eqs. (4.1)-(4.4) are the theoretical model of the time pulse data. They involve the six orbital elements through the ρ_{ik} and the two "clock parameters" δt and Δf , a total of eight parameters to be determined from the data. Simulation indicated that this is the maximum one may reliably hope to determine by straightforward least squares procedures using tracking spans of 3-6 weeks with each station averaging 60% recovery of available time pulses (typical).

In the orbit adjustment program discussed in subsection 4.3 we require the partial derivatives of the data τ_{ik} with respect to the 8 parameters. The partials with respect to Δf and δt are correctly determined only if we remember that a change Δf to f_n does two things:

(a) It changes the absolute UTC instants of all pulses and hence also the satellite-station geometry for any given pulse, i.e., ρ_{ik} .

(b) It changes $\Delta_1^* t$ and $\Delta_2^* t$.

From these facts we find

$$\frac{\partial \tau_{ik}}{\partial(\delta t)} = 1 + \frac{\dot{\rho}_{ik}}{c} \tag{4.5}$$

where $\dot{\rho}_{ik}$ is the relative range-rate at t_i . Similarly

$$\frac{\partial \tau_{ik}}{\partial(\Delta f)} = -\left(1 + \frac{\dot{\rho}_{ik}}{c}\right) \frac{k(i,1)\ \Delta_1^* t + k(i,2)\ \Delta_2^* t}{f_n} \tag{4.6}$$

Let K denote any one of the six orbital elements. Then we find the partial by the usual chain-rule logic:

$$\frac{\partial \tau_{ik}}{\partial K} = \frac{1}{c} \frac{\partial \rho_{ik}}{\partial X_i} \cdot \frac{\partial X_i}{\partial K} \tag{4.7}$$

Here $\partial \rho_{ik}/\partial X_i$ denotes the (1×3) row vector whose elements are the partials of range with respect to Cartesian satellite position, all evaluated at t_i ; the $\partial X_i/\partial K$ is the (3×1) column vector whose elements are the partials of the Cartesian satellite position components (at t_i) with respect to the orbital element K .

4.2 Editing the Data

Before we attempted a differential correction or least-squares solution for the 8 parameters discussed in the previous subsection, it was necessary to delete obviously bad data points. No entirely satisfactory method for doing this has been found. The method which finally evolved will

be described here without any claim that it is in any sense "best".

Since there are two tracking stations in the western hemisphere and two in the Pacific, DODGE was normally visible at two of the four stations at any one time. Consequently, it was possible to arrange the data for a given tracking span into "passes" and, for each pass, to list out those pulses received at <u>both</u> of the stations then observing the satellite.

This procedure involves ignoring a significant amount of the total data in practice because there are many pulses received at one of the two stations but, for various reasons, not at the other. However, the editing operates only on those pulses received at both stations.

Using our best current estimate of the orbit, we compute theoretical arrival times for the pulses at each station and form the residuals. We then subtract the residual for one station from the residual for the other. This quantity is referred to as "delta-delta". Now, although the residuals themselves are fairly large and vary with time, the delta-delta quantities effectively subtract out any time and frequency errors involved in the theoretical data, i.e., the quantity t_i of eq. (4.4), leaving only the small timing errors due to satellite orbit errors. However, an error in the experimental data that occurs at one of the two stations will appear in full in delta-delta. This statement of course ignores the possibility of compensating errors occurring at the two stations.

By visual scanning of the delta-deltas as a function of time, one can note any outliers or wild points and manually delete them from the data. Usually, by comparing residuals from each station before and after the point in question, one can assess fairly well the station at fault. Although not a hard and fast rule, a jump of 100 microseconds or more in delta-delta has been used as a basis for deletion.

4.3 Orbit Adjustment Program

The final result of the editing process described in subsection 4.2 above is a tape containing that part of the data taken during the tracking span which is "good enough" to furnish an orbit correction. To process this tape and derive the orbit correction is the function of the orbit adjustment program.

Like most orbit correction programs, this one makes iterative passes over the data, using as current estimate of the 8 parameters the values derived on the previous iteration. The initial estimate of the epoch error δt is zero. For the most part, the initial estimate of the frequency offset Δf has been obtained by making one pass over the data using $\Delta f = 0$ and then estimating a crude value of Δf that will approximately null out the predominant linear growth of the residuals in time.

On each iteration of the orbit adjustment program, processing begins by converting the current best estimates of Kepler elements at the epoch to an internal set of elements described in [4]. Numerical integration involving the geopotential forces of the earth complete through the fourth order and degree, the perturbing forces of the sun and moon and the force of the solar radiation is used to generate the ephemeris from which the "theoretical values" of the observations can be computed. The normal equation which arises in the least-squares method is solved by a routine discussed in [10]. Because the problem is nonlinear, it is necessary to iterate the solution. Breakout occurred after a fixed preset number of iterations so that the parameters could be hand adjusted, if necessary, before continuing the iteration process.

5. DESCRIPTION OF THE EXPERIMENT

The DODGE spacecraft was successfully launched into orbit on 1 July 1967 and designated as 1967-66F. The orbital characteristics that were attained were close to the nominal with an apogee of 18,161 nautical miles, a perigee of 17,959 nautical miles and an inclination of 7.027 degrees. Both Doppler and time pulse tracking measurements were obtained by the tracking stations indicating that the hardware in the spacecraft and at the stations were functioning. Because the Doppler technique had been designated as the primary tracking method, attention was first directed toward it. The results of the orbit determination procedure utilizing the Doppler data are given in [4] where it is demonstrated that the accuracy achieved was better than the goal of 100 nautical miles rms. Both antenna pointing data and measurements of the time of passage of the spacecraft into or out of the penumbra of the earth were utilized to obtain the measure of accuracy.

Study of the time pulse observations (i.e., the difference between the time of reception of the time pulse and the time of transmission from a nominal satellite clock, as a function of universal time) disclosed a phenomenon in the character of the observations that had not been expected. Since the satellite moves slowly relative to a point fixed on the earth, the data should also be both slowly varying and a continuous function of time. During tracking periods in 1968 and 1969, data obtained in the eastern hemisphere by the stations at Misawa and Smithfield did indeed have this character. However, the data obtained in the western hemisphere at both Howard County and San Jose dos Campos were of a distinctly different nature exhibiting jump discontinuities and rapid changes in amplitude. Since similar anomalies appeared in the observations at both stations at the same time the source of the difficulty had to be at the satellite and not at the stations. Further study uncovered the fact that each anomaly was correlated in time with commands transmitted to the spacecraft from the command facility at Howard County. During periods in which there were no spacecraft commands transmitted, the observations were well-behaved. The mechanism by which the performance of the timing mark generator was affected by commanding could not be uncovered.

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Since the orbit determination procedure utilizing the Doppler data yielded ephemerides of sufficient accuracy, there was little need for time pulse tracking to carry out the mission of the spacecraft. In order to perform a definitive experiment utilizing the time pulse data, it was necessary to wait for a period of time in which it would be possible to refrain from transmitting commands to the spacecraft. Such an opportunity occurred during a 51-day interval in 1970, from day 174 to day 225. During this period safeguards were employed to ensure that the spacecraft, which was in the automatic programmer mode, would not be accidentally commanded. Because the maintenance of time synchronization between the four tracking stations is imperative for meaningful time pulse data, a concerted effort to do so was undertaken. Estimates of the rms accuracy of the a posteriori calibrations were: 5 μsec at Howard County, 20 μsec at Smithfield, 50 μsec at Misawa and 100 μsec at San Jose dos Campos. The calibration of the clock at San Jose dos Campos unfortunately had to be accomplished without the benefit of clock transfers that were utilized at the other sites.

6. EPHEMERIS DETERMINATION

A total of 20 passes of data was obtained by the four tracking stations during the 51 day experiment. An a posteriori adjustment was made to the data utilizing the best estimates of the offsets of the station clocks. The data obtained at all the stations except at Howard County when plotted as a function of time were continuous and slowly varying. The data obtained at Howard County again was of poor quality. The large scatter associated with this data was attributed to poor signal strength. Since the site at San Jose dos Campos, which received the same time pulse signals as Howard County, obtained the signals at normal signal strengths, it appeared that the difficulties had to be in the receiving equipment at Howard County. Several attempts were made to localize the difficulty but these proved unsuccessful. Subsequently, the observations obtained at Howard County were not used so that the total population of tracking data consisted of the 14 passes obtained at Misawa, Smithfield and San Jose dos Campos.

By not utilizing the Howard County data, it was necessary to suspend the editing test for the data taken at San Jose dos Campos. Instead, only obviously bad data were deleted by "hand".

Initial attempts to fit both an ephemeris and satellite oscillator frequency resulted in rather poor residuals. Study of the behavior of the residuals suggested that there was significant drift of the satellite oscillator frequency. Since a frequency drift parameter was not one of the original eight fitting parameters, it was necessary to introduce it as the ninth. This would effectively make $\Delta_1^* t$ and $\Delta_2^* t$ linear functions of time. To minimize the magnitude of the modification of the software, the adjustment of the frequency parameter was not made part of the least-squares fitting procedure. Instead, it was added as a parameter which could be adjusted prior to each iteration of the least-square process. Sequentially fitting the frequency drift parameter with the other eight parameters resulted in minimizing the residuals to an rms of 54 μsec. The best estimate of the frequency drift was 0.95 x 10^{-10} parts/day which agrees to two significant places with the drift obtained as a by-product of the Doppler tracking method.

Measures of the accuracy of the orbit determination capability of the passive range tracking method are given in Figs. 6.1 to 6.5. The H, L, C, T and δ represent the corrections as a function of time that must be added to the ephemeris obtained from the passive range data to obtain the Doppler determined ephemeris. The H refers to the altitude difference, the L to the along-track difference, the C to the out-of-plane difference in the direction of the orbital angular momentum and the T represents the magnitude of the total difference which is equal to $(H^2 + L^2 + C^2)^{1/2}$. The δ represents the angular difference in the two ephemerides as viewed from the center of the earth.

The total difference, T , has a maximum value of 59.0 nm (109.2 km) and an rms of 30.9 nm (57.3 km). The angular difference, δ , has a maximum of 2.7 milliradians and an rms of 1.4 milliradians. The significant difference in the two ephemerides is in the along-track coordinate, L. Since this difference is principally a linear function of time, it arises from a difference in the periods (or semi-major axes) in the two ephemerides.

Since the Doppler determined ephemeris has been judged in [4] to be accurate to better than 100 nm rms, the ephemeris determined from the passive range data is probably no worse than $[(30.9)^2 + (100)^2]^{1/2}$ or 105 nm rms. This corresponds to an angular deviation of 4.9 milliradians rms. While these results may appear to be rather modest, when compared to what is realizable for low altitude satellites, it should be recalled that they are consistent with the original objective of 100 nm. By making modest improvements in the implementation of the passive range tracking system, the technique would be capable of providing ephemerides with a substantial improvement in accuracy. Specifically, it would be necessary to improve the synchronization of the clocks at each of the ground stations and to utilize either a higher frequency or a dual frequency signal to minimize the influence of the ionosphere on the time of propagation.

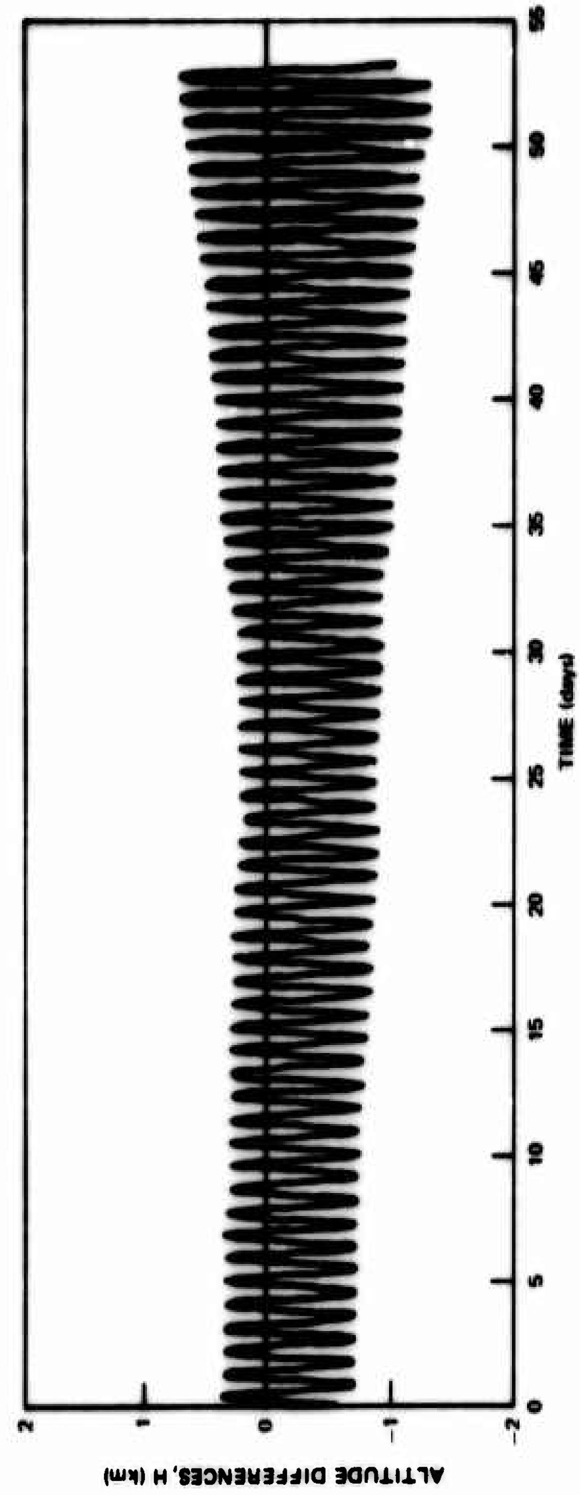

Fig. 6.1 ALTITUDE DIFFERENCES BETWEEN PASSIVE RANGE AND DOPPLER DETERMINED EPHEMERIDES

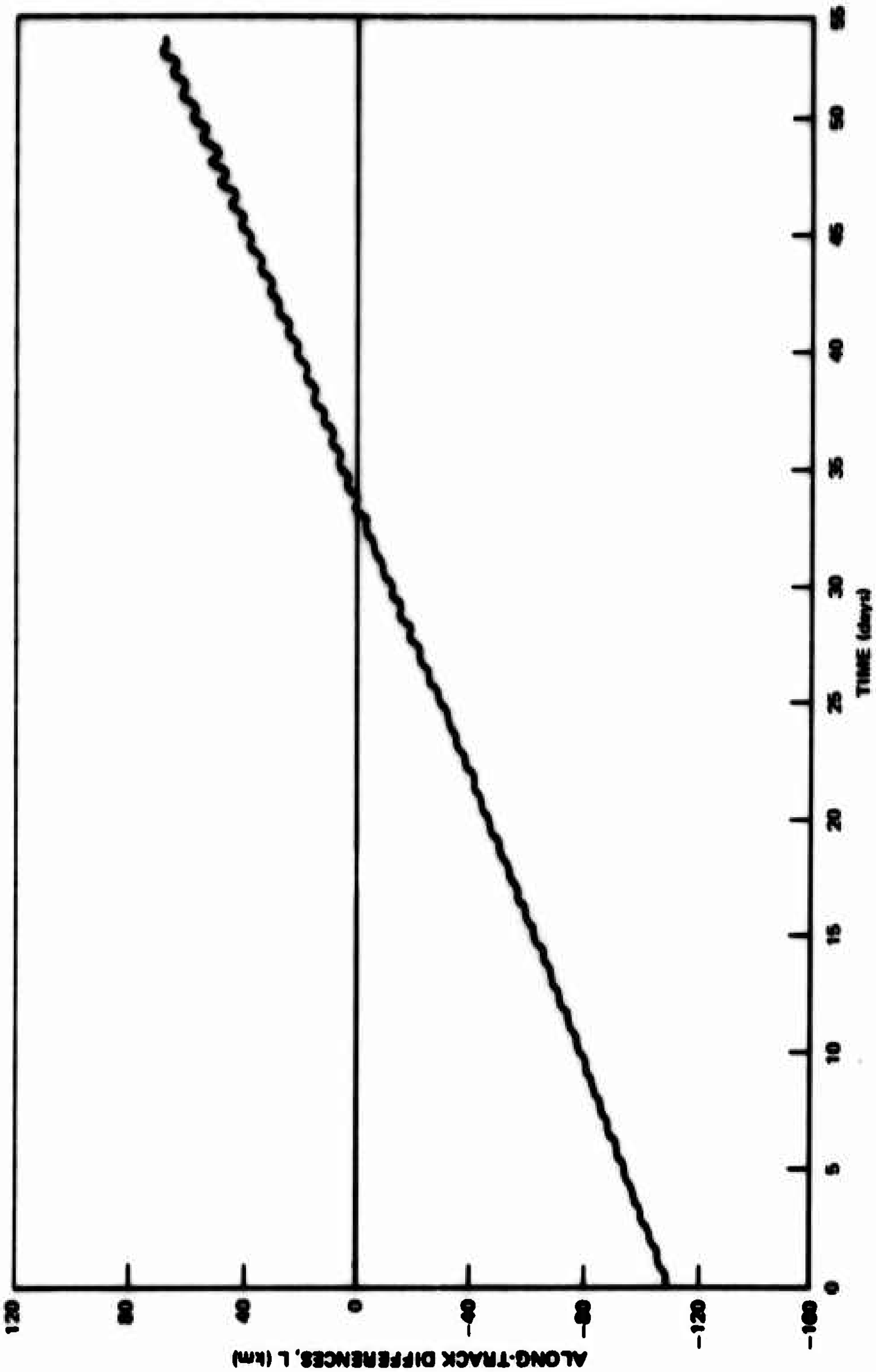

Fig. 6.2 ALONG-TRACK DIFFERENCES BETWEEN PASSIVE RANGE AND DOPPLER DETERMINED EPHEMERIDES

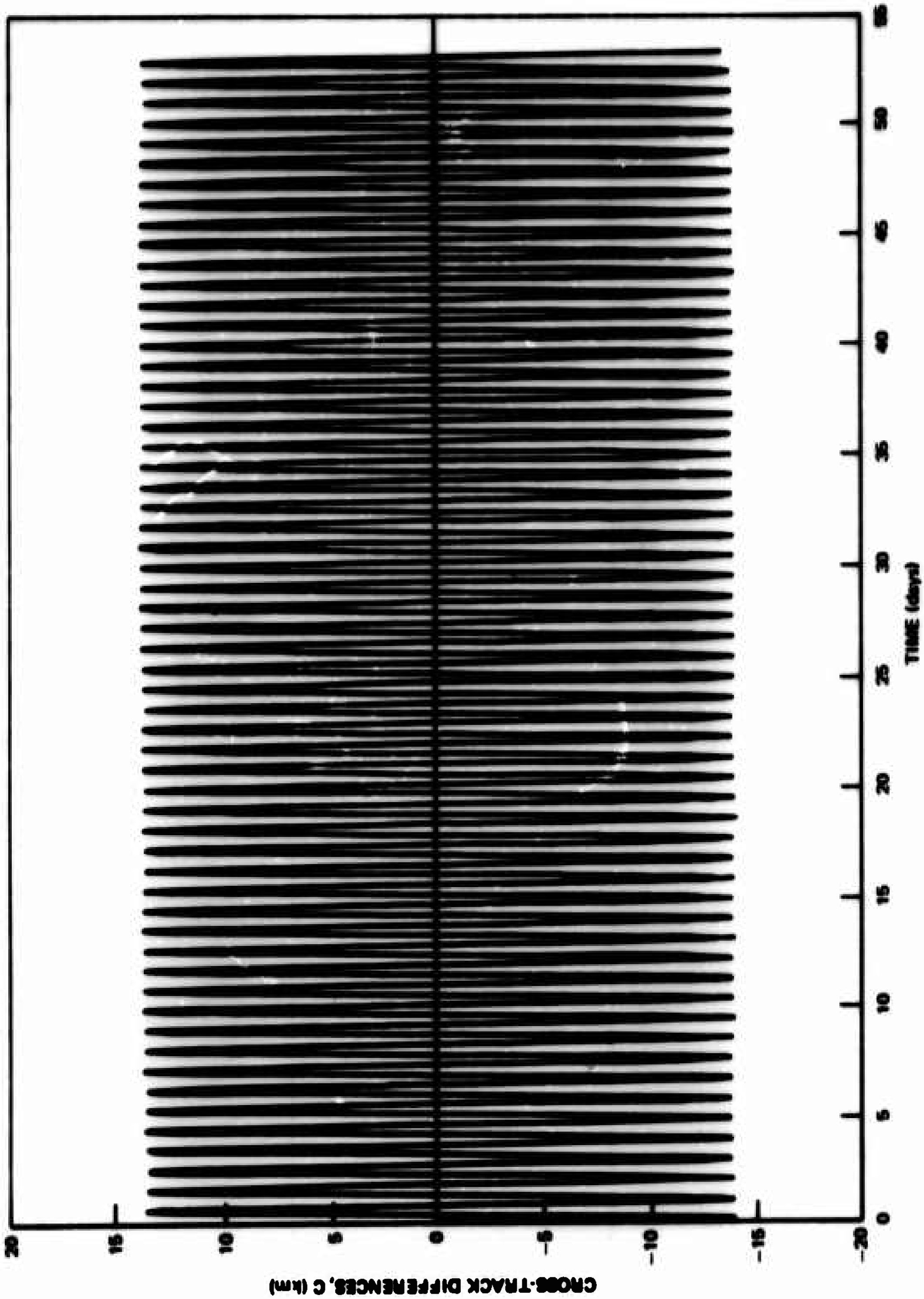

Fig. 6.3 CROSS-TRACK DIFFERENCES BETWEEN PASSIVE RANGE AND DOPPLER DETERMINED EPHEMERIDES

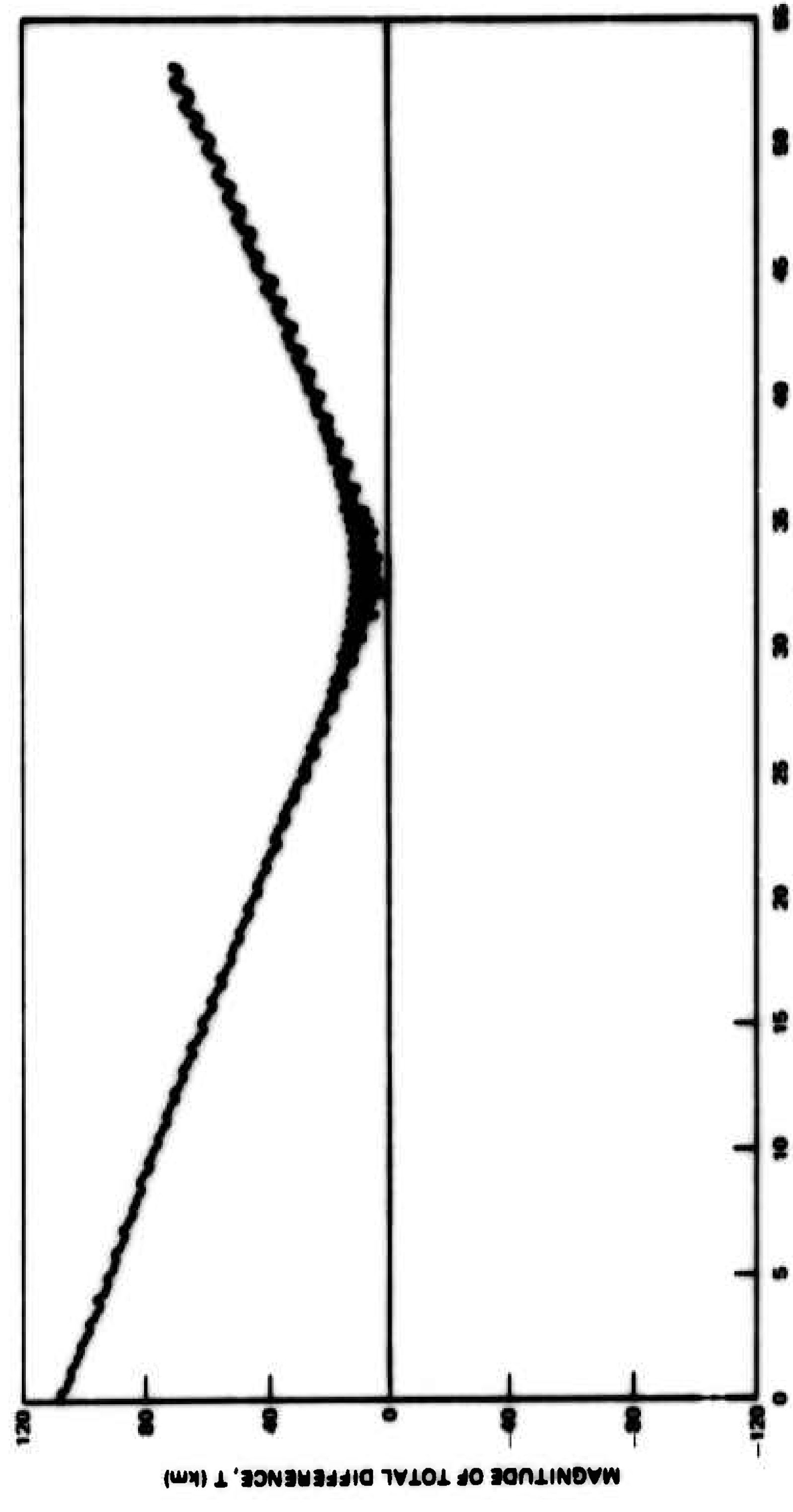

Fig. 6.4 MAGNITUDE OF THE TOTAL DIFFERENCE BETWEEN PASSIVE RANGE AND DOPPLER DETERMINED EPHEMERIDES

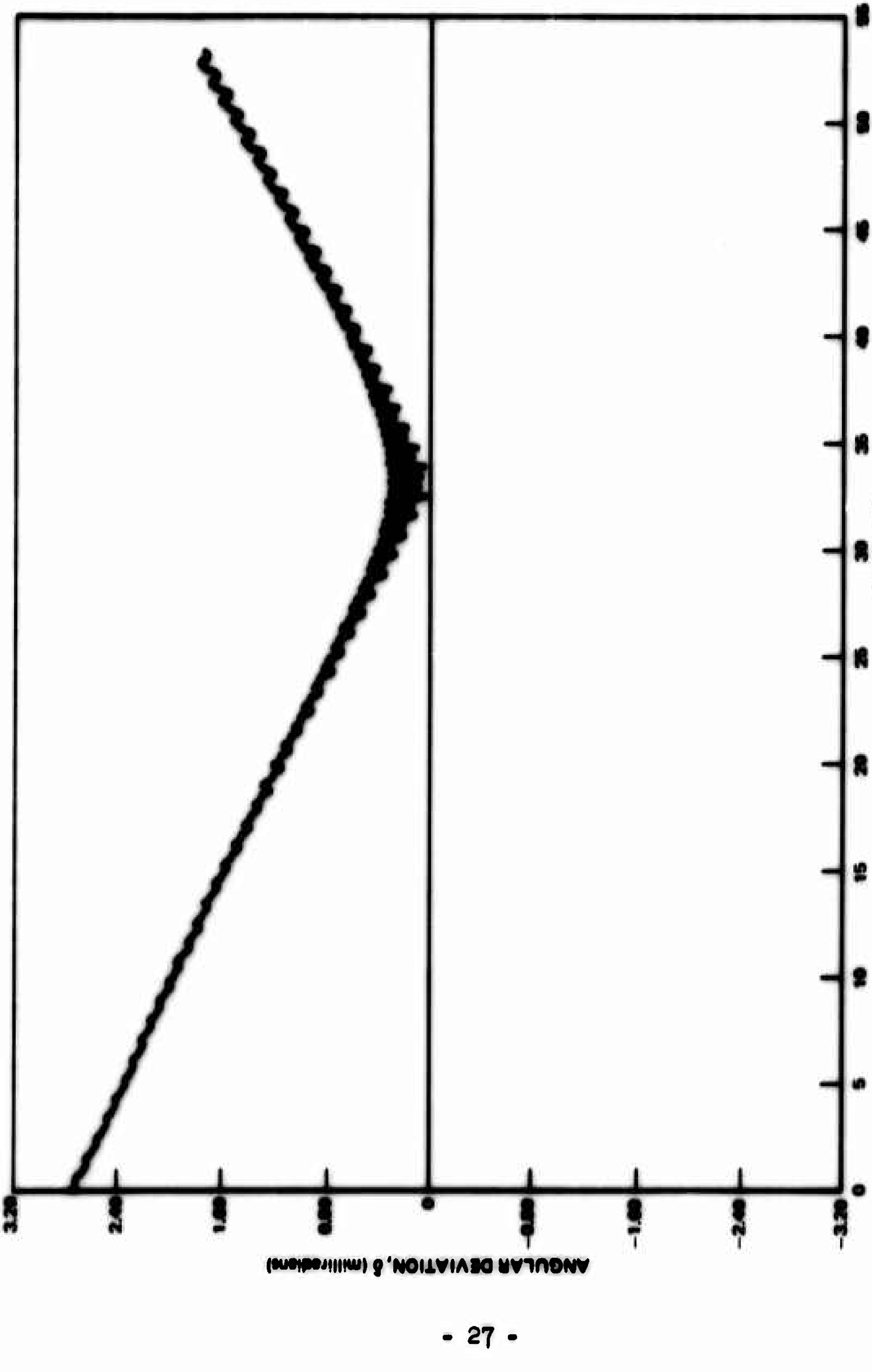

Fig. 6.5 ANGULAR DIFFERENCES BETWEEN PASSIVE RANGE AND DOPPLER DETERMINED EPHEMERIDES

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